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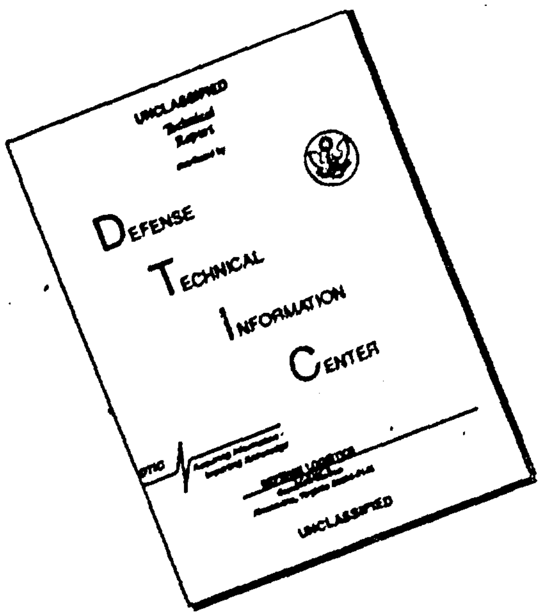

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REPORT NO. 1167
MAY 1962

A STUDY OF METALLURGICAL EFFECTS IN HIGH VELOCITY DEFORMATION OF COPPER USING ROTARY EXTRUDED LINERS (U)

M. K. Gainer
C. M. Glass

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Department of the Army Project No. 503-04-002
Ordnance Management Structure Code No. 5010.11 815
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BALLISTIC RESEARCH LABORATORIES

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Terminal Ballistics Laboratory

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ABERDEEN PROVING GROUND, MARYLAND

BALLISTIC RESEARCH LABORATORIES

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MGSainer/CHGlass/mba
Aberdeen Proving Ground, Md.
May 1962

A STUDY OF METALLURGICAL EFFECTS IN HIGH VELOCITY DEFORMATION OF COPPER USING ROTARY EXTRUDED LINERS (U)

(CONFIDENTIAL) ABSTRACT

Rotary extruded shaped charge liners have been investigated to determine the effects of preferred orientation on the optimum spin compensation frequency.

~~This investigation has shown that~~ the tangential component of collapse velocity obtained in rotary extruded liners is produced by a tangential shear in the liner wall which is induced by crystallographic slip in individual grains. The value of spin compensation frequency Ω which is obtained is therefore dependent on the orientation of grains in the liner wall, which in turn is sharply dependent on the original condition of the blank and the changes in various manufacturing parameters.

Because of the dependence of ~~Ω~~ the frequency on grain orientation it is possible to determine the optimum spin compensation frequency by measurements on a normal incidence X-ray diffraction pattern. Such measurements form the basis for non-destructive test for this type of liner.

(CONFIDENTIAL) INTRODUCTION

Rotary extruded shaped charge liners are currently being used in several low frequency spin stabilized rounds. The particular manufacturing process produces crystallographic anisotropies in the liners which may be used to study the effects of material properties on the reactions of the metal to high velocity deformation. Two regions of deformation are considered:

1. The high velocity metal flow during the formation of the cone from the blank;

2. The reaction of the cone to explosive loading to produce spin compensation.

The primary purpose of this report is to provide a quantitative explanation of spin compensation in rotary extruded liners. In addition, the reaction of the copper blanks to the shear forming is discussed, and an inspection technique is suggested in Appendix A, for determining the optimum spin frequency of the liners produced.

One of the simplest methods for obtaining high velocity metal deformation, without the presence of stress pulses or shock waves, is through the use of "rotary extrusion," a mechanized version of the standard metal spinning technique. Loading rates greater than 10^4 psi/minute are easily obtained. In this process metal flow is obtained in which the direction of load application is constant at all times. With the rapid application of load to undeformed material, the stress system and stress axis may be considered constant during the deformation process.

In rotary extrusion, a metal blank is shear formed to a rotating mandrel by a tool moving parallel to the mandrel surface. This is shown schematically in Figure 1. Mandrel rotation speeds, and the feed rate of

the tool down the mandrel, may be varied over a wide range.

The stresses applied to the blank by this process are: a bending stress produced by metal being forced to the curvature of the mandrel; an axial shear produced by the tool moving down the mandrel; and a tangential shear produced by the mandrel rotating against the tool. These are seen schematically in Figure 2. The resulting grain orientation and residual stress system in the formed cone are functions of the metal reaction to these stresses. It can be shown that the tangential shear stress is the predominant one in this process.

The general shape of stress-strain curves for metals under high velocity deformation is the subject of a large area of investigation. The type of relations proposed range from single linear laws to parabolic forms for the variation of stress with strain. Irrespective of the type of relation followed during the deformation, the preferred orientation and residual stress distribution will be functions of these relations.

In previous work various anisotropic effects in rotary extruded liners have been investigated in order to determine their influence on the spin compensation frequency obtained with this type of liner.[1] A direct correlation between the optimum spin compensation frequency and the orientation of crystallographic directions in the liner wall has been found. This relationship suggests that the tangential component of the collapse velocity is induced by slip in preferred crystallographic directions. A crystallographically dependent mechanism is further suggested by the following: It has been shown that metal single crystals react differently on different crystallographic planes, even when subjected to explosive loading.[2,3] In addition the crystallographic deformation system is generally the same as

that observed for metals under normal testing conditions, even though stresses on the specimens are a minimum of two orders of magnitude greater than the static strength of the metal.(3,4)

A series of copper cones were used in this investigation. Some cones were manufactured from copper blanks that were fully hard, and others were manufactured from fully annealed material. Variations in feed rate and mandrel speed were used. Cone angle and wall thickness were also varied. X-ray studies were conducted to determine the grain orientations throughout the specimen. The stress gradient through the wall of the specimen was used to determine qualitatively the grain rotation as a function of stress, through recrystallization experiments.

Combination of the results from the X-ray studies with the recrystallization experiments and derived equations, gives an indication of the reaction of the metal blank to the high velocity deformation imposed by rotary extrusion.

Combination of these results with the firing data obtained using liners manufactured under the same conditions gives a quantitative explanation of the mechanism through which spin compensation is achieved in these liners. The method of investigation is used to suggest an inspection technique for the manufacturing process.

(UNCLASSIFIED) EXPERIMENTAL PROCEDURE

The determination of grain orientation was made by using the Laue back reflection method. A geiger tube rotating in the plane of the diffracted cone was used to record the variation in diffracted intensities. The sample is placed in the path of the X-ray beam and can be rotated about the point of incidence in both the horizontal and vertical planes. This arrangement

is shown in Figure 3. A comparison of the intensities as measured by the geiger tube through a rate meter and recorder with a typical Laue back reflection photograph is shown in Figure 4. I_{δ_1} and I_{δ_2} are used to designate the intensities of the two maxima found in the diffraction cone. Grain orientations were determined by measuring intensities of 220 reflections for various angles of incidence of the X-ray beam in both the horizontal and vertical planes. These measurements were repeated in steps of 0.010" through the sample wall. The metal was removed through chemical etching.

Data from measurements made in the horizontal plane were plotted in polar coordinates, as shown in Figure 5. The peak intensities, in Figure 4, are plotted as vectors on either side of the zero angle line in Figure 5. Rotation of the specimen to the right or left of normal gives intensity vectors for building up the plot shown in Figure 5, which is a combination of diffraction studies of the outside and inside surfaces.

The significance of the minima can be seen by reference to the cube face drawn in the center of Figure 5. The diagonals are the $\{110\}$ planes producing the reflection, and the minima occur at the $[100]$ type pole directions, where θ is the angle this pole makes with the normal. For any angle of incidence, the diffraction peaks labled I_{δ_1} and I_{δ_2} in Figure 4, occur at 53.70° to the incident beam, symmetrically concentrated on either side of the beam in the diffraction cone. The preferred orientation is very sharp, and for the distribution shown in Figure 5, $I_{\delta_1} = I_{\delta_2}$ for 5 and 50° specimen rotation, i.e., when the X-ray beam is in the direction of an intensity maximum or minimum. For angles between 5° and 50° rotation, the

quantity $(I_{\delta_{11}} - I_{\delta_{22}})$ will increase to some maximum value and then decrease to zero at 59°. Further rotation of the incident beam past 59° will result in a change in sign of the quantity $(I_{\delta_{11}} - I_{\delta_{22}})$.

This intensity distribution may be seen as a measure of the number of grains, within the X-ray beam, that have been rotated by an applied stress. If the direction of the stress was such as to cause a counter-clockwise rotation of the grains (when seen from the cone apex), the intensity distribution would rotate in a similar direction. Intermittent normal incidence X-ray patterns taken at different stages of the grain rotation would therefore indicate a change in relative intensities similar to that already described.

Deformation due to the tangential shear causes an overall rotation of the preferred orientation that exists in the metal at the time of application of this stress. However, individual grains within the deforming metal will be rotated by different amounts. The amount of rotation for a particular stress will depend on the resolved shear stress for the slip planes in the grain. For grains at the extreme angles of orientation, rotation will follow the hypothetical curve A in Figure 6. Rotations of grains with $\boxed{100}$ poles near the normal will follow curve B.

For a single grain, θ can attain a maximum value of 45° before $I_{\delta_{11}} = I_{\delta_{22}}$, as can be seen from Figure 5. For a distribution of grains about some mean orientation P_0, the maximum value of θ is determined by the angle spread ϕ of the distribution and is given by the relationship:

$$\theta_m = 45° - \frac{\phi}{2}.$$

Therefore a difference in grain rotation throughout the distribution as

shown by the curves in Figure 6 will cause the maximum value of θ to increase as the distribution narrows. Using the method of analysis described, a rotation of grains by an applied stress will be detected as an increase of the value $(I_{\delta_1} - I_{\delta_2})$ to some maximum value, and then a decrease until $I_{\delta_1} = I_{\delta_2}$, depending on the stress level at that point. The value will then change sign and increase again.

The rotation discussed above is that in the horizontal plane of the specimen wall, produced by the tangential shear stress. X-ray studies made by rotation of the specimen above and below normal show that there is insignificant change in intensity distribution in the vertical plane. The angular width ϕ in the vertical plane does not, in any case observed, exceed 10^o. The pole to the $\{100\}$ plane of the mean of this distribution is coincident with the normal to the sample surface. Since the specimens studies were formed with rotation speeds of, for instance, 1800 rpm, and tool speeds of 15-inches/minute, this result is not unexpected. Complete $\langle 100 \rangle$ pole figure studies show unusual texture patterns clustered in a horizontal plane.

(CONFIDENTIAL) RESULTS

Theta is the angle between the mean of the distribution of [100] poles and the surface normal, as seen in Figure 5. This angle varies through the cone wall, depending on the amount of reorientation taking place during deformation. The reorientation is a function of the reaction of the blank material to the applied stress. The tangential shear stress may be considered to vary linearly through the cone wall, as shown in Figure 2. It has been shown that the tangential force applied in this process is directly proportional

to the feed rate in inches per revolution.[5] Consequently, the tangential stress will also be directly proportional to the feed rate. The specimens reported here were produced with a constant mandrel speed, and a varying tool feed, so that the variation produced in the specimens is directly dependent on the tangetial stress. Figures 8 and 9 show the variation of Θ with x, the distance from the inside surface of the cone to the point considered, for specimens made from annealed and hard blanks.

The curves for specimens made from soft blanks, Figure 8, show a grain rotation that has caused a narrow distribution of orientations. For higher feed rates, the greater applied stress produces a larger variation in Θ. Figure 9, for hard blank specimens, shows little change in Θ between the two feed rates, for the first half of the cone wall. The effect of the tangential shear is large in the outer half of the wall only. The preferred orientation in the inner half of the specimen wall is caused by reorientation of the original blank texture by the axial shear and bending imposed on the blank.

Recrystallization studies of the specimens show a variation in grains per unit area with position through the specimen wall, as seen in Figure 10. To a close approximation, the number of grains per unit area will be a direct function of the amount of plastic flow that has taken place at a point in the metal[6], and therefore a direct measure of the reaction of the blank material to the applied tangential stress.

As seen in Figure 10, the number of grains per unit area for cones made from annealed blanks is linear through the wall. For cones made from hard blanks, the number of grains per unit area becomes a constant approximately half-way through the wall, again indicating that the tangential shear stress

has not caused plastic deformation in this region. For both hard and soft blanks, the variation is linear in the region where the tangential stress causes plastic flow.

Figure 11 shows the variation of Θ with F, or the tangential stress, for soft blank cones. For hard blank cones the Θ vs F curve is a straight line, as indicated on Figure 11.

(CONFIDENTIAL) CONCLUSIONS

A. Reaction of the Copper to High Velocity Deformation During Shear Forming.

Combining the results: Θ vs x; grains/area vs x; and Θ vs F gives an indication of the metal reaction under high velocity loading. The variation in Θ is a direct measure of the strain variation during deformation. The variation in number of grains per unit area shows the regions of influence of the tangential shear stress, and also is a direct function of the strain the metal was subjected to.

The reaction of the hard blanks, in the region where the tangential shear stress causes deformation, is linear; that is, $\sigma_t = K\Theta$. Since $\Theta = K\,\epsilon$, it can be concluded that the reaction of strain hardened copper to high velocity deformation follows a linear stress-strain law: $\sigma = K\,\epsilon$.

The fully annealed copper reacts differently. For soft blanks, the maximum value of Θ is proportional to the difference in the plastic strain developed in differently oriented grains in the distribution. The curve for soft blank copper in Figure 11 reflects this. This curve is a parabola; that is

$$\sigma_t = K\,\Theta^{1/2}, \text{ or } \sigma = K\,\epsilon^{1/2}$$

Only qualitative conclusions have been drawn. Experiments relating θ and strain in a more quantitative manner are required before quantitative stress-strain curves can be plotted. In addition, data should be obtained from the recrystallization work to give a more useful relation between the number of grains per unit area and the metal flow taking place.

However, this work demonstrates one of the major reasons for the different results obtained in the reaction of metals to high velocity deformation. Annealed copper follows a parabolic law, as shown by Bell for the case of dynamic comparison tests[4,6], but strain hardened copper reacts according to a linear stress-strain relationship.

B. Reaction of the Copper Liners to Explosive Loading: Spin Compensation.

It has been shown that the effect of rotary extrusion is to cause a tangential rotation of grains in the direction of the tangential shear stress; the significance of this effect in producing non-radial metal flow during the collapse of the explosively loaded shaped charge liner will now be considered.

Plastic deformation of single crystals takes place by slip along certain crystallographic planes. If the crystal is not subjected to any constraining forces, the resulting change in shape and lattice rotation is a direct function of this mode of deformation. However, in a polycrystalline aggregate, the deformation in each grain is influenced by grains surrounding it which are either not yet deforming, or are deforming in different directions because of differences in orientation. The heavy preferred orientation found in the liner wall makes it possible, for the purposes of calculation, to replace the distribution of orientation by a one orientation, represented by a single

crystal having the orientation of the mean of the distribution. Therefore, the angle θ is the angle the [100] pole of this grain makes with the normal in the tangential direction. It will also be assumed that at the stress levels encountered in shaped charge collapse, all of the possible slip systems in a given grain will be active. This has been shown to be the case for single crystals deformed at high velocities.[8]

Observations on explosively loaded single crystals indicate that crystallographic effects influence the metal deformation as soon as the initial compressive pulse reflects back into the specimen from the free surface. Therefore, it will be assumed that in a shaped charge liner, crystallographic slip will take place after the first stress pulse is reflected from the inside surface.

A diagram representing grains near the inside surface of a liner is shown in Figure 12. The diagonal lines represent slip planes. The difference in orientation between successive grains is determined by the slope of the θ vs x curve. As the reflected stress pulse moves through grain A slip begins. The grain is free to deform in the direction of the inside surface. The tangential component of velocity is zero as shown in the vector diagram in Figure 13a.

Grain B is severely restricted in its deformation. It cannot stretch tangentially because it is constrained by the convergence of grains around it toward the axis. It is restricted from deforming in the direction of grain C by the fact that the stress pulse has not reached that region. Therefore, it must at least partially deform in the direction that grain A is deforming. Slip planes in grain B will then rotate to align themselves with those in grain A.

The vector diagram of velocities in this instance is shown in Figure 13B. Grains A and B both have the same vertical component of velocity V_o, but because of their different orientations have different initial tangential components. Planes in grain B rotate with a velocity V_r to try and align themselves with planes in grain A.

As the reflected stress pulse progresses toward the outside surface, planes in each grain will align themselves with those at the inside surface. Since the angle between the first slip planes and those at some point in the liner wall increases as the distance x increases (at least for one half the wall thickness), the tangential component of velocity will also increase. V_t is then, as obtained from the vector diagram in Figure 13C given by

$$V_t = V_o \tan \Delta\Theta$$

where $\Delta\Theta$ is the angle between the initial slip planes at the inside surface and those at some point in the liner wall.

For a typical hard blank liner, $\Delta\Theta$ is 3^o for x = .030". If the collapse velocity V_o is 2×10^5 mm/sec,

$$V_t = 2 \times 10^5 \tan 3^o = 1.04 \times 10^4$$

let r = 40mm

$$\text{then } \Omega = \frac{1.04 \times 10^4}{80\pi} = 41.8 \text{ cps}$$

This type of liner has an observed value of Ω of 40 cps.

The spin compensation frequency Ω, therefore depends on the slope of the Θ vs x curve through the inner half of a liner. It has been shown that for hard blank liners this slope is not changed in the rotary extrusion process. Therefore, hard blank liners should have the same value of Ω regardless of the

magnitude of the tangential shear during manufacture. Table I shows values of Ω obtained from penetration rotation firings of hard blank liners made with different feed rates.

TABLE I

Feed Rate m/rev	Mandrell Speed rev/min	Ω cps
6	1200	44
12	1200	40
24	1200	40
40	1200	40

It has been shown that the slope of the Θ vs x curve for liners made from soft blanks is dependent on the tangential shear stress applied during manufacture. The spin compensation frequency should then vary with the tangential stress in a similar manner. This is indicated by the Ω vs NF/t curves in Figure 14. The curves A and B represent liners made on two different machines. The tool contact area was greater for machine A than for machine B. The tangential stress was therefore lower and the value of Ω lower than that obtained with machine B for the same value of NF/t and mandrel speed. The values of Ω for these curves were obtained from penetration rotation firings.

There are two possible methods for conserving angular momentum in this system. The first case is that described previously.[1] The stress pulse is considered to have a preferred particle velocity in the direction of the close packed planes, acquiring this preferred motion upon reflection from the inside surface. This gives rise to a preferred rotation in the gasses, when the stress pulse reaches the outside surface, as in the case of liners with interior flutes.

Another way of considering the problem depends on the angular velocity,

V_t, given to the material by the grains attempting to align themselves in the direction of flow of the inside surface. Essentially, the mechanism of flow is the same as in the first case. Reflection of the stress pulse from the inner surface gives rise to preferential flow on the planes in grain A in Figure 12. Figure 13 shows the torque that has been imposed on planes rotating towards the preferred flow direction generated by the movement of the inside surface. If the θ vs x curves in Figures 8 and 9 are examined, it is seen that θ reverses direction at some point through the wall. This indicates the planes rotate in the opposite direction to arrive at the preferred flow direction. Metal above and below the point of reversal will be rotating in opposite directions, therefore $V_{t_1} m_1 = V_{t_2} m_2 + V_{t_3} m_3$ or, after canceling constants,

$$(\tan \Delta\theta_1)(\Delta r) = (\tan \Delta\theta_2)(\Delta r_2) + (\tan \Delta\theta_3)(\Delta r_3)$$

where region one is from θ at $x = 0$ to $\dot{\theta}$ at $x =$ reversal point; region two goes from θ at $x =$ reversal point to θ original; and region three is from θ original up to the outside surface.

Calculations show the following:

TABLE II

Cone	$(\tan \Delta\theta_1)(\Delta r_1)$	$(\tan \Delta\theta_2)(\Delta r_2) + (\tan \Delta\theta_3)(\Delta r_3)$
Hard blank - 40 cps	7.45	7.93
Soft blank - 10 cps	6.5	5.3
Soft blank - 25 cps	4.35	4.3

The implication is, therefore, that the slug and jet are rotating in opposite directions, since the metal that goes into each comes from portions of the cone wall that have resultant velocities in opposite directions.

(CONFIDENTIAL) SUMMARY

The tangential component of collapse velocity obtained in rotary extruded liners is produced by a tangential shear in the liner wall which is induced by crystallographic slip in individual grains. The value of spin compensation frequency Ω which is obtained is therefore dependent on the orientation of grains in the liner wall.

or soft blank liners, the orientation of grains is a function of the tangential shear applied during manufacture. Therefore, the value of ω is dependent on the magnitude of this stress which for a particular machine can be approximated by

$$\sigma_t = KF$$

where F is the feed rate in inches/rev.

Since Ω is a function of grain orientation, a determination of the spin compensation frequency for a particular liner can be made by use of the relationship

$$\Theta = K(I_{\delta_1} - I_{\delta_2})$$

where Θ is the average angle of orientation of the grains in the liner wall at a particular point and I_{δ_1} and I_{δ_2} are the intensities of the maxima in the diffracted cone of x-radiation for normal incidence X-rays.

This type of test is reliable for all types of rotary extruded liners if the X-rays measurements are made in the liner wall where Θ approaches its maximum value. It is therefore a destructive test.

For soft blank liners, the orientation of grains at the outside surface is dependent on the magnitude of the tangential shear in the same manner as

those at other points in the liner wall. This makes it possible to make a non-destructive X-ray test on soft blank liners manufactured from the same machine. Hard blank liners will have a spin compensation frequency that will be constant for a wide range of conditions, so spot tests can be made.

The change in orientation is chiefly due to the tangential shear. Therefore, the effect produced by this stress in the horizontal plane will be considered only. It can be considered as a rotation imposed on the orientation already obtained through axial shear and bending.

M. K. GAINER

C. M. GLASS

(CONFIDENTIAL) APPENDIX A (U)

(CONFIDENTIAL) INSPECTION METHODS

It has been shown that the value of $(I_{\delta_1} - I_{\delta_2})$ at normal incidence is a direct indication of the amount of rotation that has been given to the grains in the liner wall.

Therefore,

$$\Theta = K(I_{\delta_1} - I_{\delta_2})$$

It should be possible therefore, to determine the spin compensation frequency ω by measuring $I_{\delta_1} - I_{\delta_2}$ for a normal incident X-ray made at a point in the liner wall where Θ approaches its maximum value.

Figure 17 shows $I_{\delta_1} - I_{\delta_2}$ vs Ω for liners made from both hard and soft blanks. These measurements were made at approximately 1/3 the wall thickness of the liner from the outside surface. The values of Ω for these liners were obtained from penetration rotation firings and flash X-ray measurements.

A spot check on liners could be made by manufacturers in a similar manner using the type of X-ray instrumentation described in this report. An indication of the reliability of this method can be seen from the sample data shown in Figure 15. These curves were obtained in the inspection of one T-384 liners and one T-300. On the basis of this inspection a value of ω of 35 cps was predicted for the T-300 liner and a value of 2) cps was predicted for the T-384 liners. These predicted values were within ± 5 cps of the value later obtained from penetration rotation firings.

For soft blank liners, the tangential plastic deformation takes place through the entire wall of the liner. The grain orientation at the outside surface is therefore as much dependent on the tangential shear as that inside

the liner wall. Therefore, a non-destructive test can be made on soft blank liners to determine their spin compensation frequency.

The curve of $I_{\delta_1} - I_{\delta_2}$ vs Ω for the outside surface of soft blanks is shown in Figure 17 for liners made with the same machine.

The surface orientation is more subject to change by slight changes in tool angle and shape, (contact area), than the inside orientation. Therefore, a non-destructive test can be made only on liners from a specific machine, whereas, a destructive test gives an absolute value of Ω regardless of blank hardness or machine parameters.

Measurements of the type mentioned above should be made with an instrument similar to the one described in this report. However, since only normal incidence X-rays are needed for this inspection technique, the instrument may be modified in the following manner. The geiger tube may be made stationary and be fixed at the proper angle with the X-ray beam (53.4°) to receive the diffracted radiation. The liner can then be rotated about the axis of the X-ray beam in such a way that the surface is always normal to the beam. Such a modification should prove more adaptable to production line inspection.

The present criteria for inspecting the rotary extruded liners, to determine their optimum spin compensation frequency, is the angle which lines scribed on the inside surface of the blank are twisted during deformation. This is in effect a measurement of the amount of tangential plastic deformation given to the inside surface of the liner during manufacture. For hard blank liners no tangential plastic deformation takes place at the inside surface. Any angle of twist is produced by the combination of axial shear and bending only. It is therefore obvious that the angle of twist is a completely

inaccurate criteria for measuring Ω for hard blank liners.

For soft blank liners, the variations in the firmness of contact between the formed liner and the mandrel surface can appreciably alter the amount of plastic flow taking place at the inside surface. The angle of twist is therefore not an accurate measure of plastic deformation at points higher up in the liner wall, and will not accurately indicate the optimum spin compensation frequency.

The existence of the Ω vs stress relationship for soft blank liners provides a basis for determining the manufacturing parameters to be used in forming liners which are to have a given value of ω. Such a curve can be obtained either from existing data or by obtaining ω for liners whose manufacturing parameters are known. However, in doing so it is important to keep the area of contact and the blank material constant. Small changes in the tool angle can change the area of contact significantly enough to produce a considerable change in the value of the spin compensation frequency obtained for a given value of NF/t.

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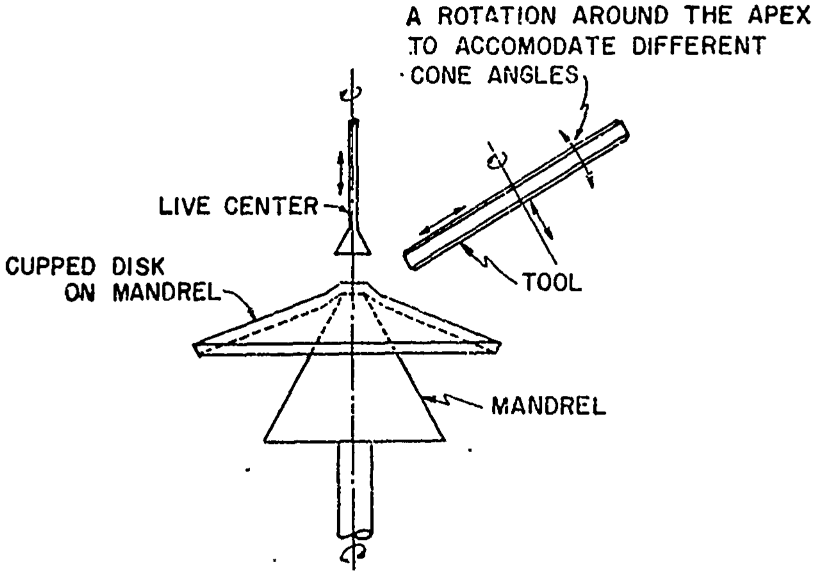
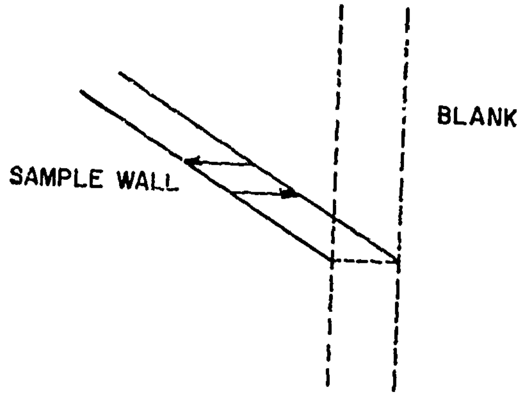
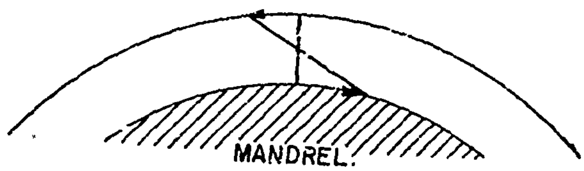


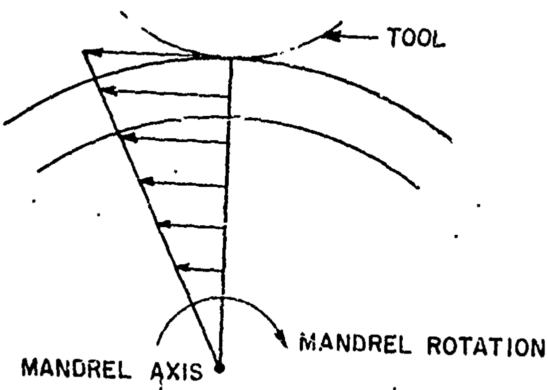
FIG. I - SCHEMATIC DIAGRAM OF THE ROTARY EXTRUSION EXTRUSION PROCESS.



AXIAL SHEAR STRESS



BENDING STRESS



TANGENTIAL SHEAR STRESS

FIGURE 2
VARIOUS STRESSES PRESENT IN THE PROCESS

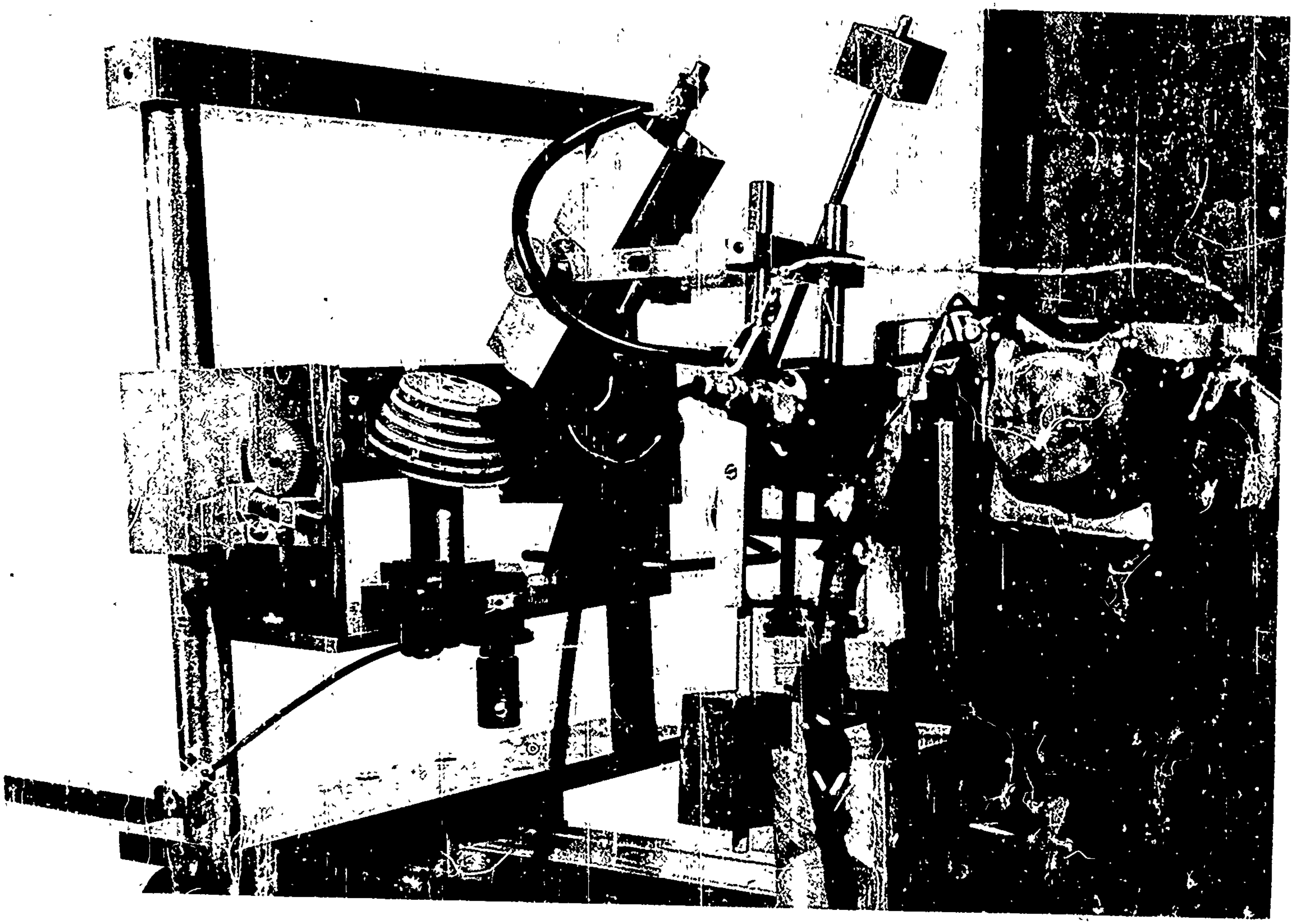
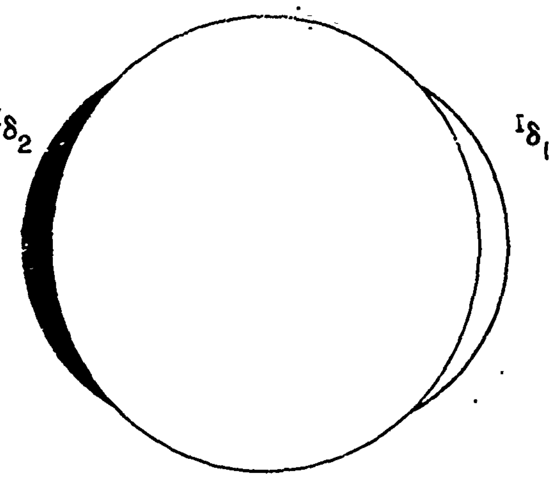
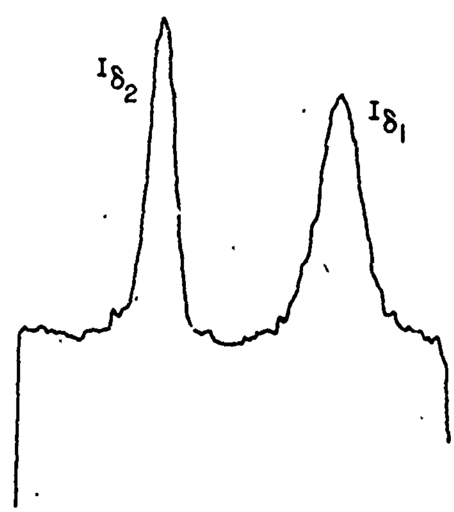


FIGURE 3. BACK REFLECTION GONIOMETER



PHOTOGRAPHIC INTENSITY



GEIGER TUBE INTENSITY

FIGURE 4
TYPICAL CHART RECORD AND BACK-REFLECTION PHOTOGRAPH

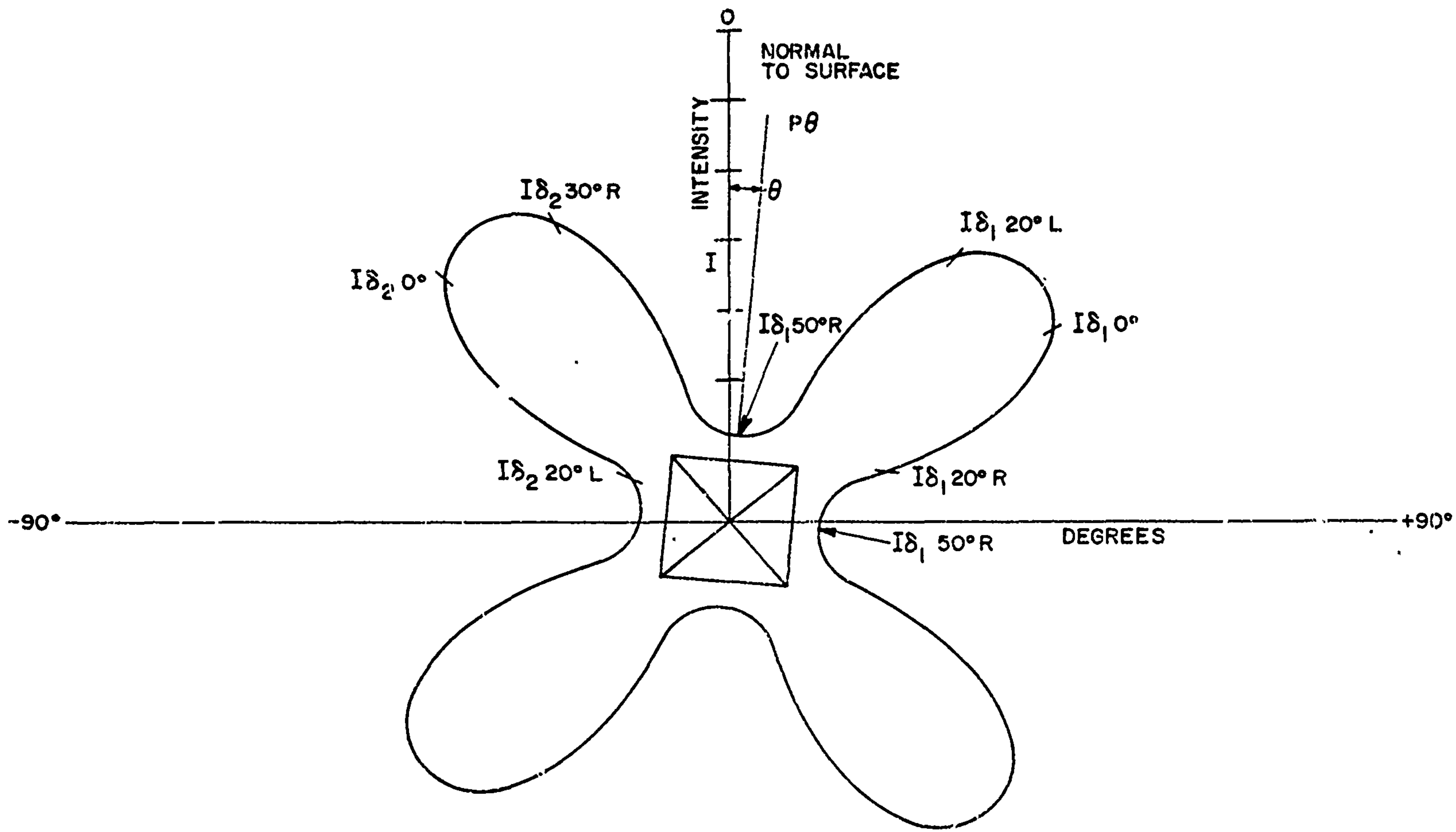


FIGURE 5
INTENSITY PLOTS OF THE DIFFRACTION PEAKS — POLAR COORDINATES

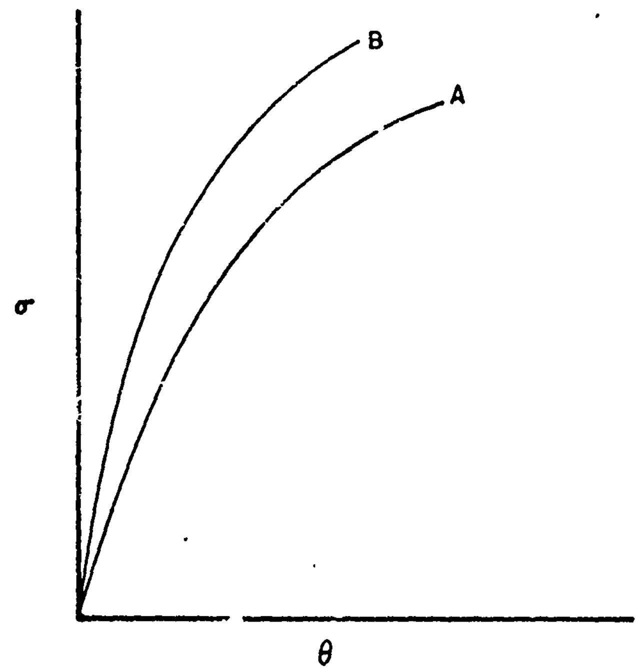
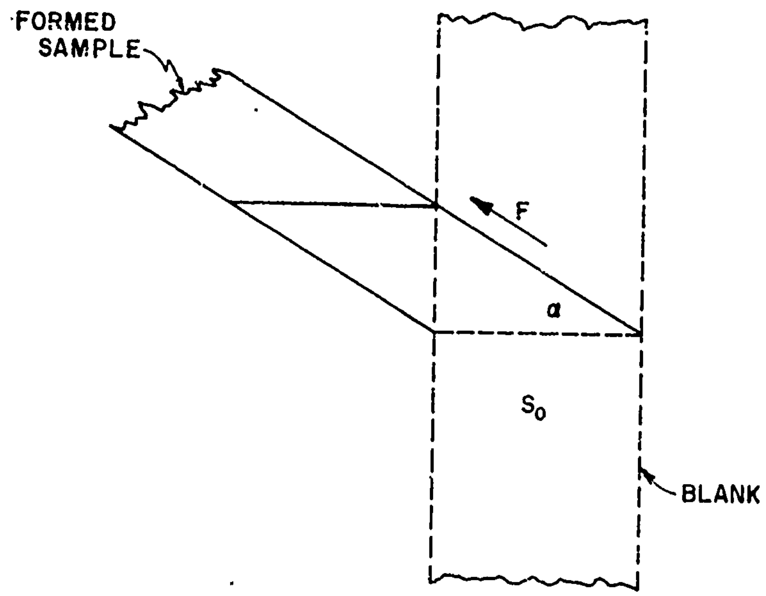


FIGURE 6
POSSIBLE STRESS – THETA VARIATIONS



F = TOOL FEED IN INCHES/REV.
S_0 = BLANK THICKNESS

FIGURE 7
SCHEMATIC OF THE METAL FLOW

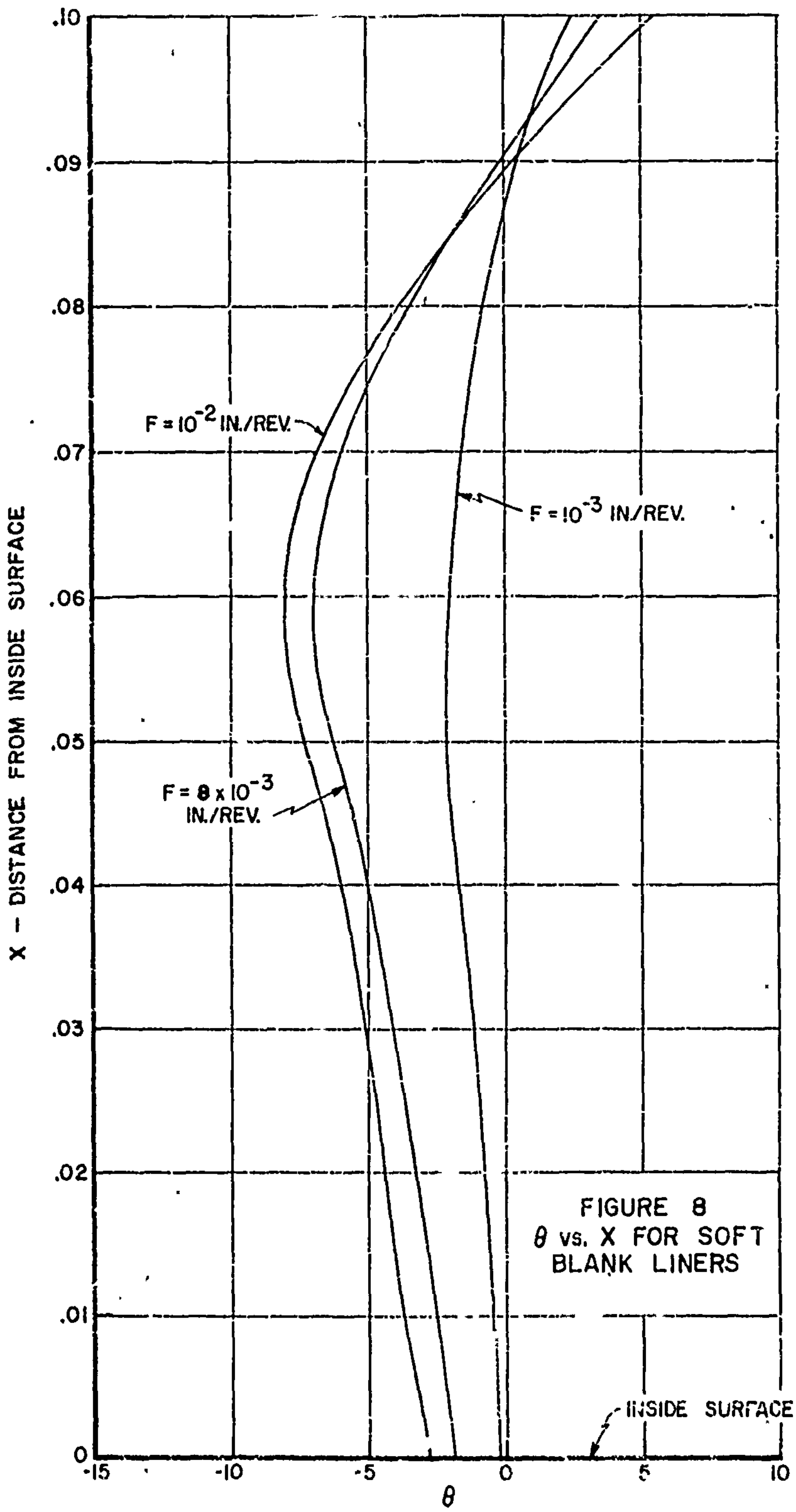


FIGURE 8
θ vs. X FOR SOFT BLANK LINERS

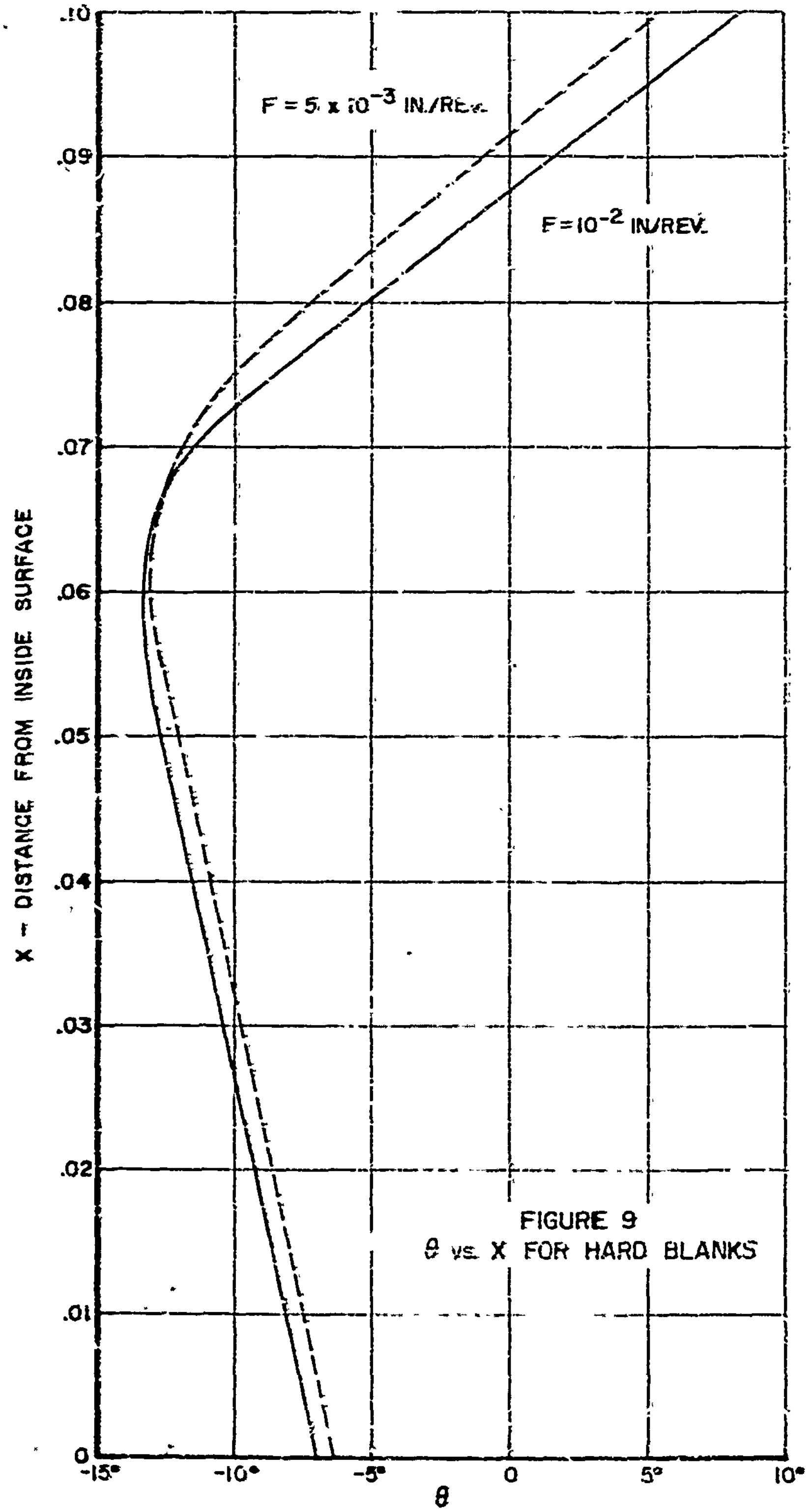


FIGURE 9
θ vs. X FOR HARD BLANKS

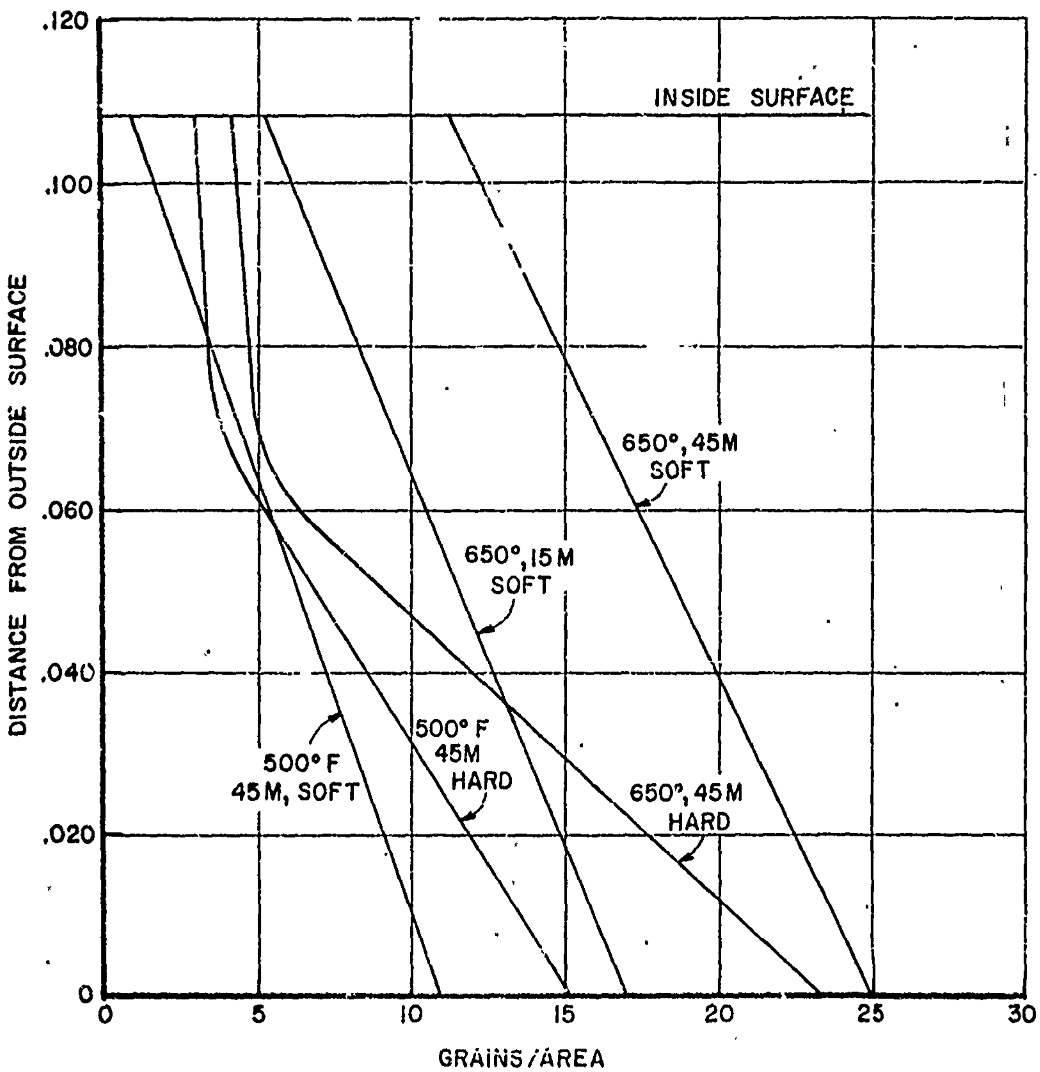


FIGURE 10
CHANGE IN GRAIN SIZE DURING ANNEAL

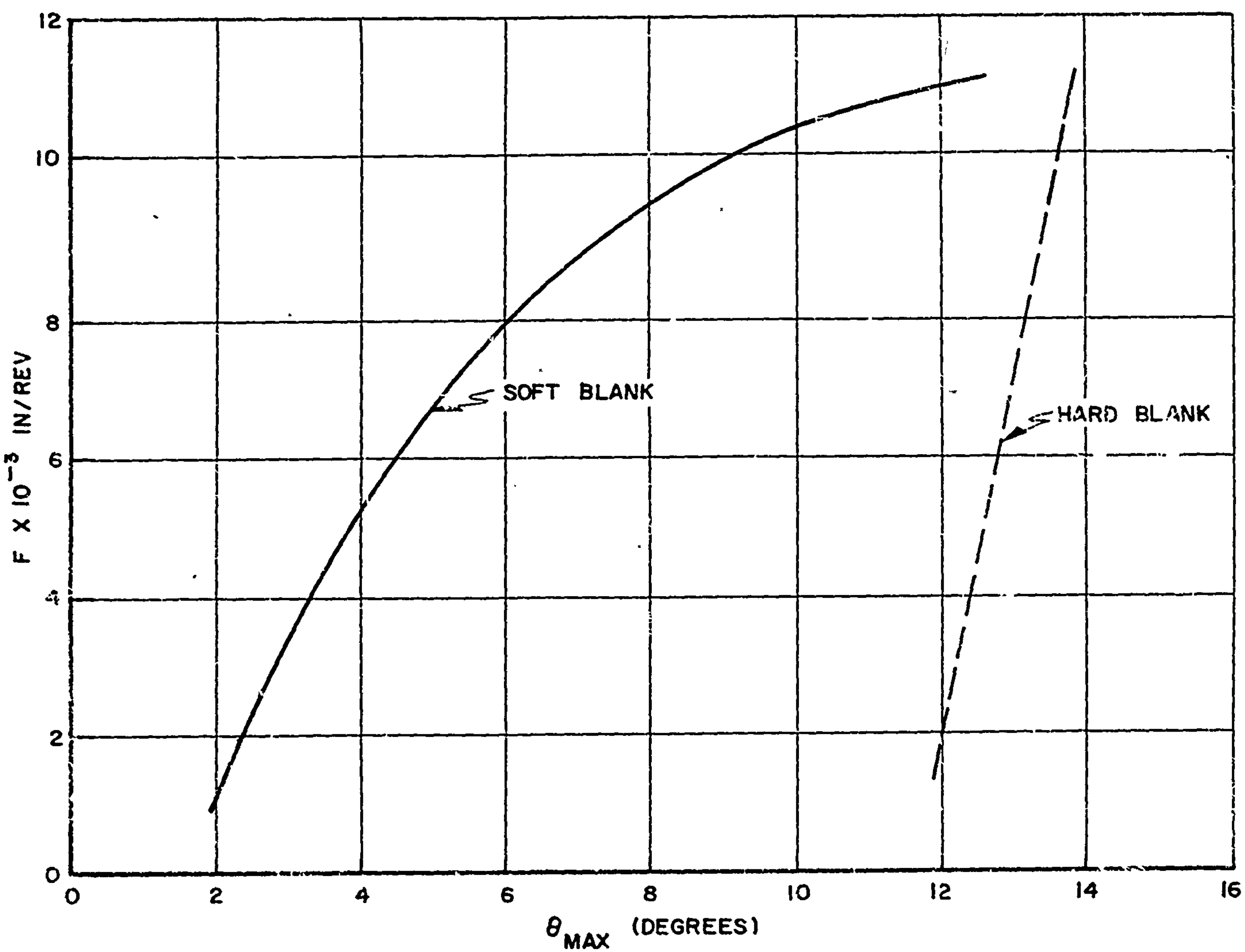


FIG. 11. θ_{MAX} VS. F FOR CONES MADE FROM SOFT AND HARD BLANKS .

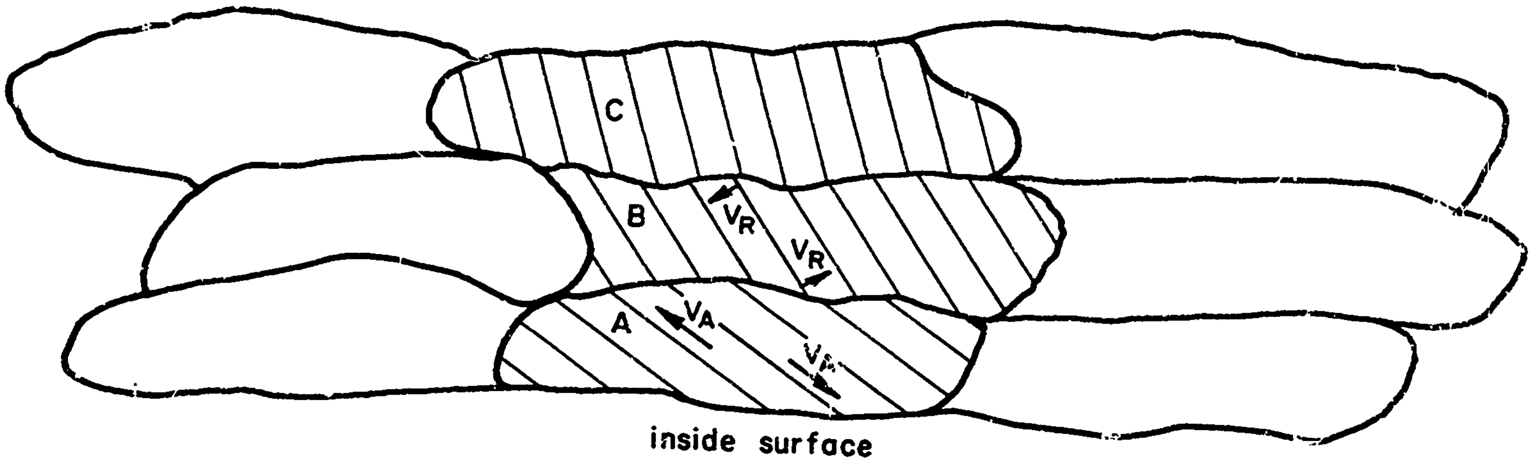


FIGURE 12

SLIP DURING LINER COLLAPSE

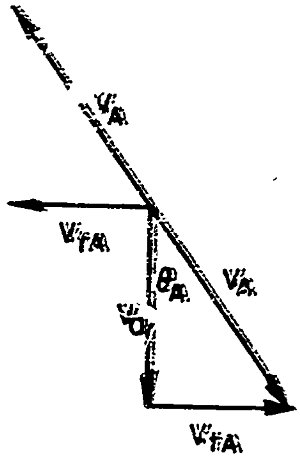


FIGURE 13A

SLIP IN GRAIN A

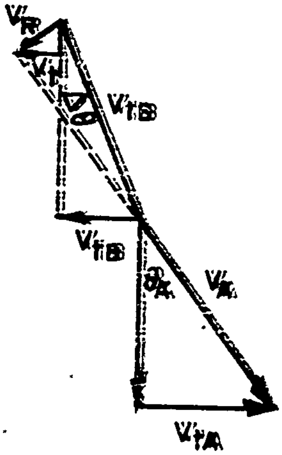


FIGURE 13B

SLIP IN GRAIN B

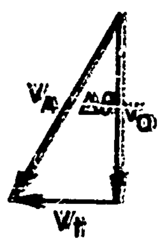


FIGURE 13C

TANGENTIAL VELOCITY
VECTOR

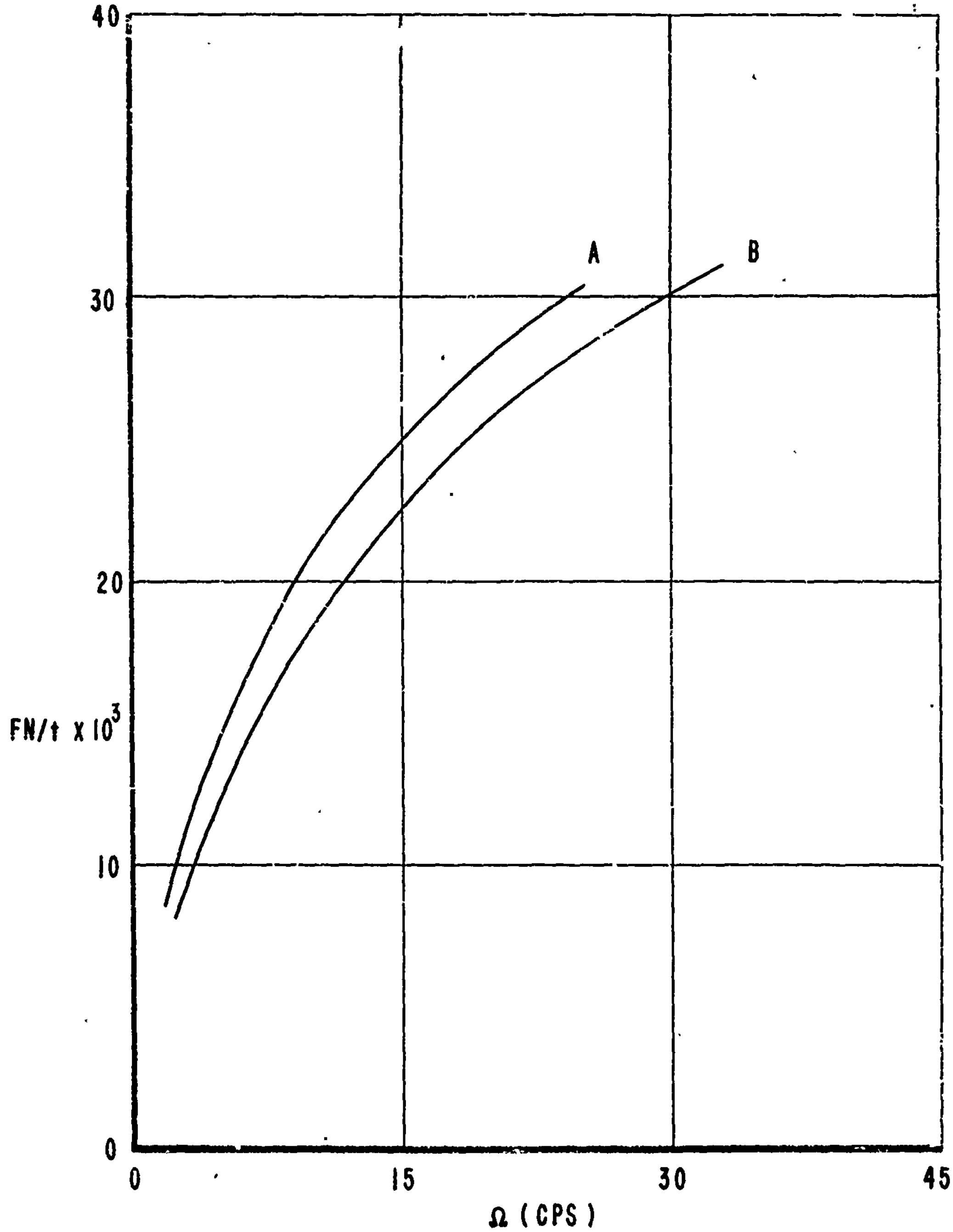


FIGURE 14
(CONFIDENTIAL) OPTIMUM SPIN COMPENSATION FREQUENCY VS. FN/t (U)

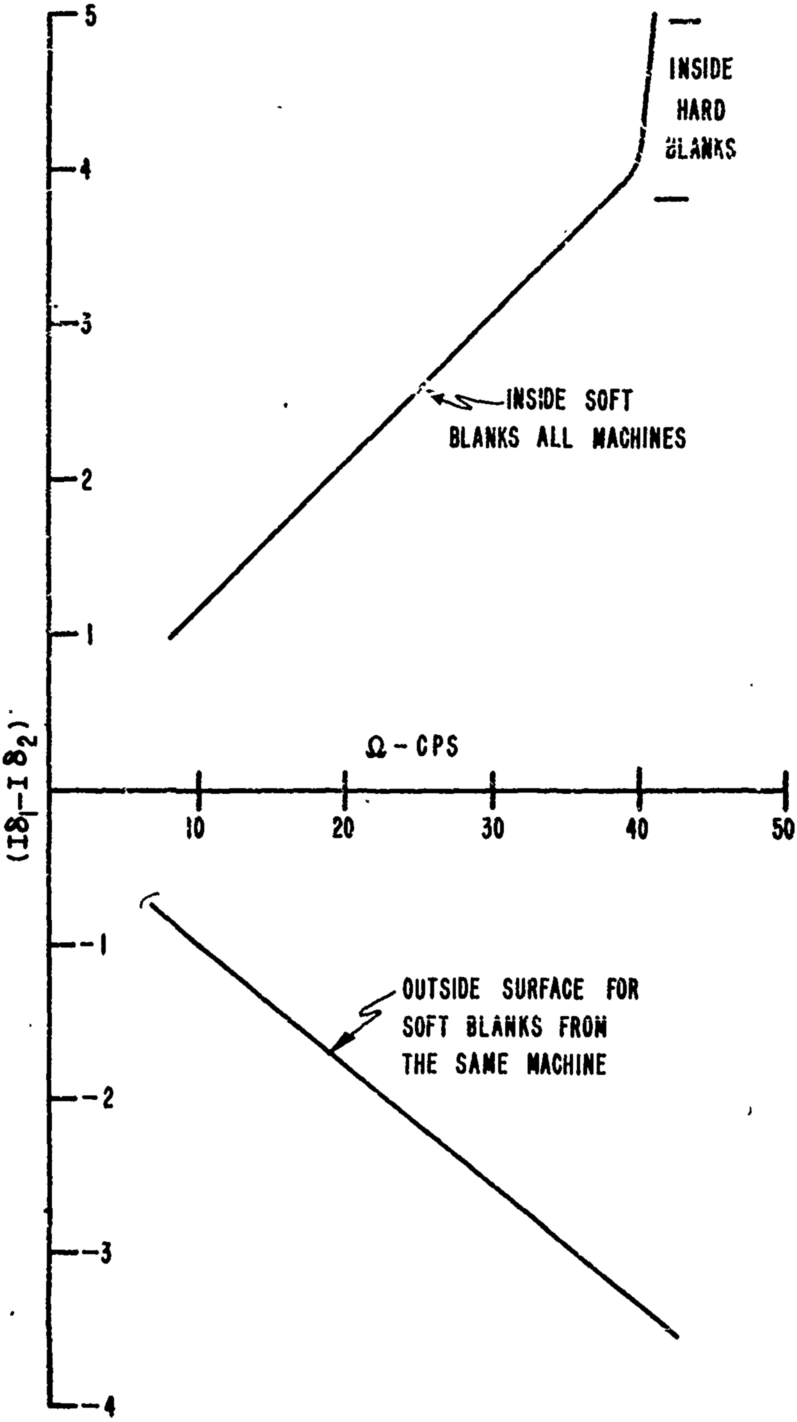


FIGURE 15

(CONFIDENTIAL) $(I\delta_1 - I\delta_2)$ VS. Ω FOR HARD AND SOFT BLANK LINERS (U)

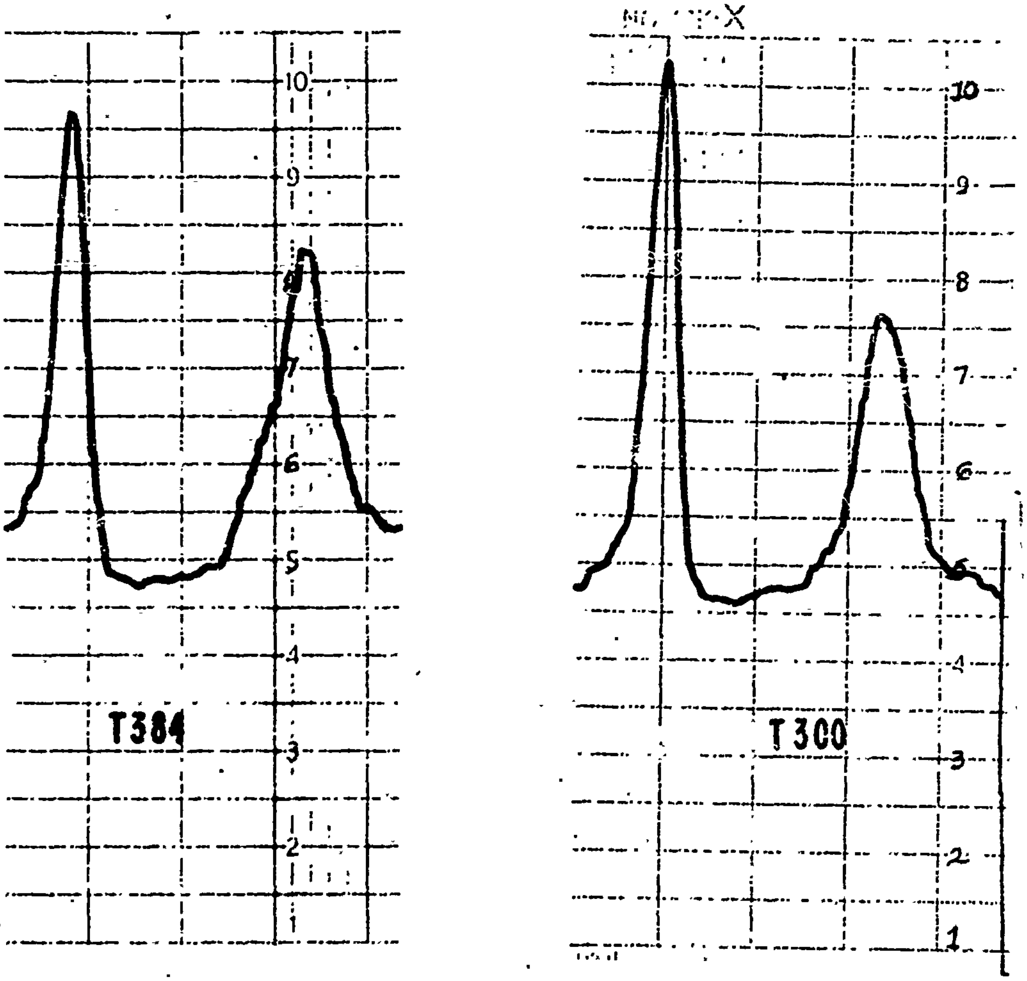


FIGURE 16
SAMPLE DATA FOR T300 AND T384 LINERS

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M. K. Gainer and C. M. Glass

Shaped charge liners - Performance
Metals - Deformation
Metals - Extrusion

BRL Report No. 1167 May 1962

DA Proj No. 503-04-002, OMSC No. 5010.11.815
UNCLASSIFIED Report

A non-destructive method for assessing the quality of shaped charge liners is described. The method is quantitative and provides a means for establishing quality control procedures. A theoretical discussion and experimental data are presented.

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